Title
ANALYSIS OF ONE HUNDRED BEVATRON T+ PARTICLES

Author
Haddock, Roy P.

Publication Date
1956-02-07

UCRL 3284

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

ANALYSIS OF ONE HUNDRED BEVATRON τ^+ PARTICLES

DISCLAIMER

UCRL-3284
Physics Distribution

UNIVERSITY OF CALIFORNIA

Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

ANALYSIS OF ONE HUNDRED BEVATRON τ^+ PARTICLES

Roy P. Haddock

February 7, 1956

Printed for the U. S. Atomic Energy Commission

ANALYSIS OF ONE HUNDRED BEVATRON τ^+ PARTICLES

Contents

ANALYSIS OF ONE HUNDRED BEVATRON τ^+ PARTICLES

Roy P. Haddock

Radiation Laboratory
University of California
Berkeley, California

February 7, 1956

ABSTRACT

One hundred τ^+ mesons, obtained from nuclear emulsion stacks exposed to the K^+ beam at the Bevatron, are analyzed for (a) Q value of the tau decay (b) possible values of the spin-parity of the tau. A Q of 75.13 ± .20 Mev is obtained. The corresponding tau mass is 966.5 ± .74 m_e. The analyses by Dalitz and Fabri were used to assign possible spin-parity values to the tau. The case of 0- gives the best agreement with the observed energy and angle distributions.

ANALYSIS OF ONE HUNDRED BEVATRON τ^+ PARTICLES

Roy P. Haddock

Radiation Laboratory
University of California
Berkeley, California

February 7, 1956

I. INTRODUCTION

One hundred τ^+ mesons ($\tau^+ \rightarrow 2\pi^+ + \pi^- + Q$) found in the systematic scanning of three emulsion stacks have been analyzed.*

The Q values have been studied and an average Q obtained. The most important systematic errors were considered and their limits assigned to the Q value.

The distribution of decay configurations has been compared with the analyses developed independently by Dalitz[1, 2, 3] and Fabri.[4] All cases of spin and parity of the tau that are also possible for the $K_{\pi 2}$ were considered up to and including spin five.

---

* Twenty-four of these τ^+'s were included in the data presented at the 1955 Conference on Elementary Particles held at Pisa, Italy.

1 R. H. Dalitz, Proc. Phys. Soc. 64, 710 (1953).

2 R. H. Dalitz, Phil. Mag. 44, 1068 (1953).

3 R. H. Dalitz, Phys. Rev. 94, 1046 (1954).

4 E. Fabri, Nuovo Cimento 11, 479 (1954).

II. EXPERIMENTAL ARRANGEMENT AND SCANNING TECHNIQUE

The strong-focusing spectrometer[5] at the Bevatron was used to select nearly monoenergetic positive K particles and focus them on three emulsion blocks.

The emulsion blocks were stacked (without tissue paper between the pellicles), backed with 1/2-inch bakelite, and held together with bolts passing through the bakelite and emulsion. The stack edges were then machined to close tolerances to permit accurate measurements (for volume and density determinations).

The scanning was done by the track-following method. Tracks in a grain count interval were selected at a region of the stacks where K particles would have several centimeters of residual range. These tracks were then followed to their ends and the particles were identified by their decay mode. This method is thus unbiased in regard to the tau-decay configuration.

III. MEASUREMENT OF THE Q

A. Method

The densities and average plate thicknesses were determined from the dimensions and weight of the stacks.

The average plate thickness was used to compute the chord between points where there was either an integrated 10° change of direction in the plane of the emulsion or a visible change in the diving rate. The range of the pions was taken to be the sum of these chords when corrected for air gaps between pellicles. A full discussion of the range measurements is given in Section III-B.

The range-energy relation given by Barkas and Young[6] was used. It is based on Vigneron's parameters; in particular, the mean ionization potential of 322 ev is used to extrapolate to high velocity. The relation is for C.2 emulsion of density 3.815 g/cm^3 at a relative humidity of 55%.

---

5 L. T. Kerth and D. H. Stork, Phys. Rev. 99, 641 (A) (1955).

6 W. H. Barkas and D. M. Young, "Emulsion Tables. I. Heavy-Particle Functions," University of California Radiation Laboratory Report No. UCRL-2579 (rev.) Sept. 1954.

B. Errors

1. Alignment

X-ray marks placed in the stacks before processing provide an accurate means of aligning the plates after development. Generally the position of neighboring plates is known to within 25 microns, but there may be a systematic shift to the stack. To eliminate or reduce any systematic shift of this type the coordinates of the X-ray marks were measured with a microscope stage and used when necessary. The error in alignment is then the error in estimating the center of the X-ray mark.

2. Distortion and Rub-off Errors

The ranges were computed, not as the sum of path lengths in each plate, but as a chord between points where the track changes direction by 10°. Then the distortion and rub-off errors to first approximation enter only as errors in the position of the tau decay and pion decay. An error in the position of an intermediate point such as to increase one chord length will reduce the following chord length by a like amount to the first order. The distortion and rub-off errors are then negligible.

3. Range Shortening

The percent difference between the arc and chord lengths along a pion track was estimated to be 0.48% in range or 0.25% in energy. This estimate is good to 30%. The uncertainty of 30% is due mostly to an uncertainty in how closely the 10° criterion was followed. Then the average Q of the tau obtained by measuring chords should be increased by 0.19 Mev to account for the effect of range shortening.

4. Air Gaps

The average densities of the emulsion stacks, obtained from their measured areal densities σ and the thickness of the stacks, were 0.7% to 1.1% less than 3.826 g/cm^3. The latter is the density for Ilford G.5 emulsion when it is shipped from the factory. From measurements of individual pellicles of fresh emulsion it is evident that there is little water loss through the shipping wrappings. There also should be little change in the density during stacking of the emulsion or through the edges of the machined stack. The difference between the average density of the stacked emulsion and of individual pellicles is attributed to air gaps between pellicles. The air gaps (about 5μ thick on the average) increase the total stack thickness above its true value and so reduce the stack density.

Let t_m and ρ_m be the measured average plate thickness and density for the stack, and t_t and ρ_t the true average thickness and density of the emulsion. The ranges of the pions can then be computed as follows:

(a) t_m is used to obtain the shrinkage factor. This gives the length of the track through both emulsion and air.

(b) The true density ρ_t is assumed to be 3.826 g/cm^3.

(c) The average air gap thickness, t_a, is taken to be

$$t_a = t_m - t_t = \sigma \{1/\rho_m - 1/\rho_t\}.$$

(d) The range in emulsion alone, R_E, is then obtained from

$$R_{E_i}/R_i = Z_{E_i}/Z_i = Z_i - Na_i t_a/Z_i, \qquad (1)$$

where R_{E_i} is the length of the ith chord in emulsion,

R_i is the length of the ith chord in emulsion and air,

Z_{E_i} is the vertical height between chord ends in emulsion,

Z_i is the corresponding height through air and emulsion,

Na_i is the number of air gaps traversed.

Then

$$R_E = \Sigma_i R_{E_i}.$$

Any uncertainty in ρ_t is due to an uncertainty in the equilibrium value of the relative humidity of the emulsion. Since the stopping power of emulsion per g/cm^2 is a slowly varying function of its water content (relative humidity), an error in ρ_t leads to a relatively smaller error in Q. The effect of an error in ρ_t on the Q values is given (see appendix) by

$$\Delta Q/Q = -0.046 \Delta \rho/\rho. \qquad (2)$$

Barkas and Young[6] give the density of emulsion at 35% relative humidity as 3.90 g/cm^3. This is the upper limit of the emulsion density, and the measured stack density is the lower limit. Inspection of Eq. (2) shows that for 1% uncertainty in the emulsion density the uncertainty in the average Q will be 0.05%, or ΔQ = 0.04 Mev. The uncertainty in Q due to the uncertainty in emulsion density is therefore negligible.

C. Results

An average Q of

74.94 Mev + .19 Mev (range shortening)

$^{+.04}_{-.07}$ Mev (uncertainty in water content of emulsion)

± .18 Mev (standard deviation of the average Q)

± .07 Mev (uncertainty in the measurement of the stack density)

or 74.94 + .19 ± .20 Mev

was obtained for 67 taus. For these taus all three pions stopped in the stack and none of the pions made a large-angle scatter. Figure 1 shows the distribution of Q values. This distribution is quite consistent with a normal distribution (which is also plotted).

The corresponding mas of the tau (in electron mass, m_e) is

966.1 m_e + .37 m_e (range shortening)

$^{+.08}_{-.14}$ m_e (uncertainty in water content of emulsion)

± .36 m_e (standard deviation of the average Q)

± .62 m_e (standard deviation of the pion masses)

± .14 m_e (uncertainty in measurement of stack density)

or 966.1 + .37 ± .74 m_e.

The pion masses found by Barkas, Birnbaum, and Smith[7] were used. These masses are

$$m_{\pi^+} = 273.3 \pm 0.3\ m_e,$$

$$m_{\pi^-} = 272.8 \pm 0.4\ m_e,$$

where the errors indicated are standard deviations.

---

[7] W. H. Barkas, W. Birnbaum, and F. M. Smith, "The Mass Ratio Method Applied to the Measurement of L-Meson Masses and the Energy Balance in Pion Decay," University of California Radiation Laboratory Report No. UCRL-3147, Sept. 1955. Also to be published in Phys. Rev., Jan. 15, 1956.

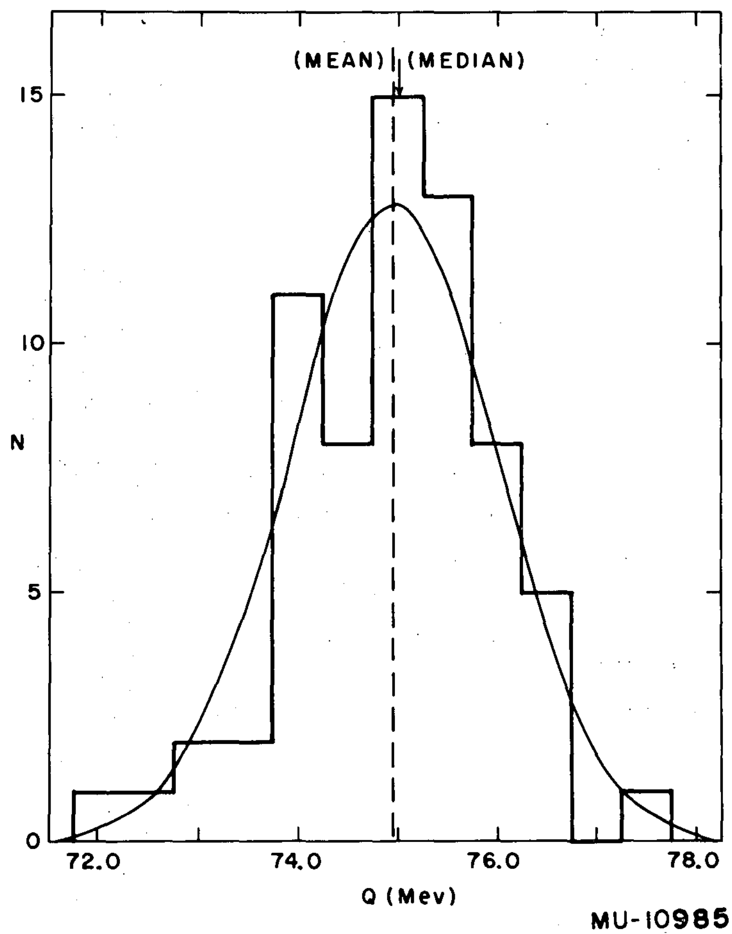

Fig. 1. Plot of the distribution of Q values for 67 taus which had all three pions staying in the stack and none of the pions making a large-angle scatter. The average Q is 74.94 Mev and the median is 75.0 Mev. The distribution is fitted with a normal curve and the agreement is observed to be quite good.

IV. SPIN AND PARITY

The dependence of the decay amplitude on the spin and parity of the tau has been independently investigated by Dalitz[1,2,3] and Fabri.[4] Amaldi[8] has compared all available tau data with the analyses by Dalitz and Fabri, and concludes that the spin-parity of the tau may be 0-, 2-, 4-, etc., and possible 3-. I would like to review some of the analyses by Dalitz and Fabri in order to discuss the so-called ambiguous cases.

A. Analysis by Dalitz and Fabri

Relative coordinates are used to describe the decay configuration of the three final-state pions. The relative coordinate $\vec{r}$ is proportional to the distance between like pions and $\vec{r}\,'$ is proportional to the distance between the unlike pion and the center of mass of the like pion system. The momenta $\vec{p}$ and $\vec{p}\,'$ are the conjugate momenta and $\vec{\ell}$ and $\vec{\ell}\,'$ the corresponding angular momenta ($\vec{\ell}$ is even by Bose-Einstein statistics).

If the orientation of the decay-plane normal and the rotations of the decay configuration about the decay-plane normal are neglected, then only two independent variables are necessary to determine the decay configuration. These are taken to be $|\vec{p}\,'|$ and $\cos\theta = \frac{\vec{p}\cdot\vec{p}\,'}{pp'}$. The conservation of angular momentum requires that the spin of the tau be the vector sum of $\vec{\ell}$ and $\vec{\ell}\,'$, i.e., $\vec{J}_\tau = \vec{\ell} + \vec{\ell}\,'$. The conservation of parity requires that the parity of the tau be the product of the intrinsic parity of the three pions and their orbital parity, i.e., $P_\tau = (-1)^3(-1)^{\ell+\ell'} = (-1)^{\ell'+1}$.

If the Coulomb and pion-pion interactions are neglected, the final state of the tau can be thought of as three independent pions. The tau is coupled to three pion states having the same spin and parity. These three pion states are characterized by various values of ℓ and ℓ'. There are a variety of states of three pions having the same spin and parity, and therefore the final state of the tau will be a linear combination of all these three pion states.

---

[8] E. Amaldi, Proceedings of the conference on Elementary Particles at Pisa, Italy to be published as a supplement to the Nuovo Cimento.

In order to estimate the relative probabilities for decay into different final states, Dalitz and Fabri assume that the probability amplitude of these states is proportional to the value of the corresponding wave function in the volume occupied by the tau. The radius of this volume is chosen to be the tau Compton wave length, which is small compared with the wave length of the emitted pions. The free-pion wave functions near the origin are approximated by the lowest-order term, i. e., the spherical Bessel function of order ℓ, $j_\ell \simeq (\rho r)^\ell/(2\ell + 1)!!$. Using these assumptions, one derives the magnitude of the relative decay amplitudes. Telegdi[9] has pointed out that if final-state interactions are to be neglected then, on the basis of time reversibility, the ratios of the relative decay amplitudes are real. The sign, however, cannot be obtained without further assumptions about the details of the structure of the tau.

The decay amplitudes are shown to be small except for those states for which $\ell + \ell' = \text{min}$. Then the distribution of decay configurations is uniquely determined if only one state has $\ell + \ell' = \text{min}$. If there are several states with the same $\ell + \ell' = \text{min}$, the decay configurations also depend on the relative phases between these states. The latter are then the ambiguous cases.

A single state with $\ell + \ell' = \text{min}$ exists for the cases of tau spin and parity 0-, 1+, 1-, 2+, 3-. For all other cases (except 0+, which is not a possible final state for three pions) there are two or more final states with $\ell + \ell' = \text{min}$.

B. Comparison of Angular and Odd-Pion Energy Distributions with the Analysis by Dalitz and Fabri

1. Discussion

One hundred τ^+ mesons were found systematically by the track-following method described in Section II. Where only two pions stayed in the stack or where a pion made a large-angle scatter, the Q of these taus was assumed to be 74.9 Mev and the lost or scattered pion was assigned an energy accordingly. (The conservation of momentum was also used to verify this assignment.)

---

9 V. L. Telegdi, private communication.

All the theoretical distributions* were computed by use of the nonrelativistic approximation. In this approximation the relative phase between three pion states appears only in the cos θ distribution, and not in the unlike-pion-energy distribution. The relative phase is taken to be 0 or π for the nonunique cases.

Figures 2 and 3 show the theoretical distributions for the unique cases, i.e., 0-, 1+, 1-, 2+, 3-. Figures 4 and 5 show the theoretical distributions for the nonunique cases, 2-, 3+, 4+, and 5-. In these only two three-pion states have the same $\ell + \ell' = \min$. Also shown in each figure is the corresponding observed distribution.

2. Statistics

To determine the significance of the results of comparing two or more theoretical hypotheses with a sample of finite size, it is necessary to consider the probability (a) that the sample comes from any one of the theoretical distributions, and (b) that a hypothesis will be rejected in favor of another, on the basis of (a) when in fact the hypothesis is false. If χ^2(chi-square) is the statistic used for the comparison then the probability of (a) is the Pearson probability and the probability of (b) is called the power.[10] The power depends only on the theoretical hypotheses, the sample size, and-of course-the confidence level of (a). Clearly for a pair of hypotheses (I and II) there are two powers, i.e., the probability of rejecting I in favor II if in fact I is false, and vice versa.

Table I gives the Pearson probabilities for cases in which the tau spin-parity is 0-, 1+, 1-, 2+, 2-, 3+, 3-, 4+, and 5-. Table II gives the power for the χ^2 test for comparing 0- with the remaining cases at the 5% confidence level of the Pearson probability. Five intervals were used for both the cos θ and odd-pion energy distribution. As cos θ and $T_{\pi-}$ have independent χ^2 distributions, the χ^2 for each distribution may be added, and the corresponding Pearson probability and power are calculated for the sum of their degrees of freedom.

---

* All theoretical distributions were obtained from formulas 8 and 14 of Fabri's paper.[4]

10 See, for example O. Kempthorne, Design and Analysis of Experiments, (New York, Wiley, 1952) p 219-223.

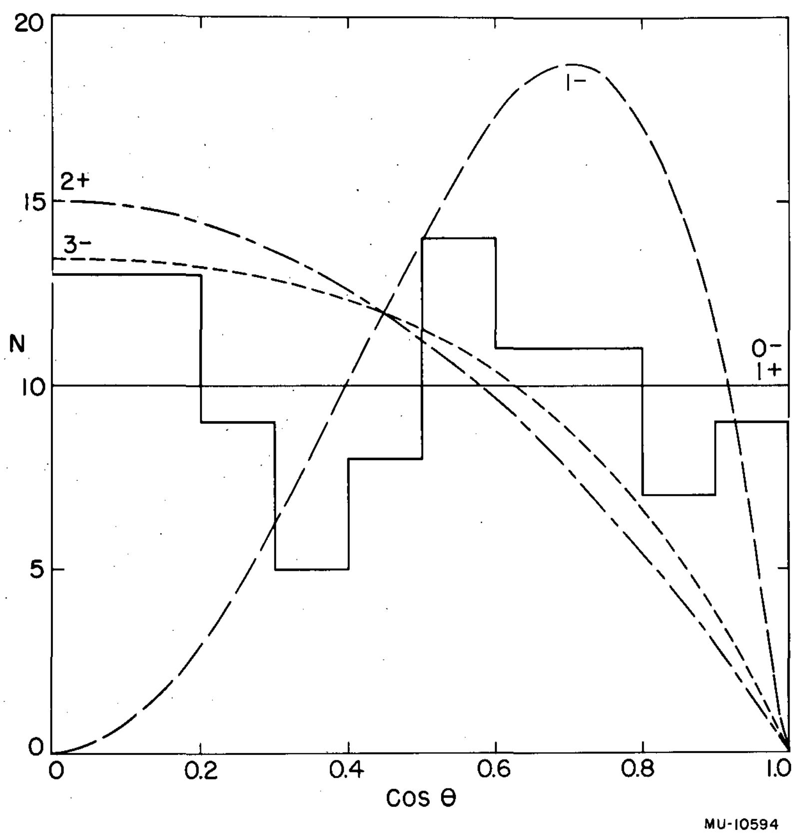

Fig. 2. Plot of expected cos θ distribution for tau spin-parity 0-, 1+, 1-, 2+, 3-. Also shown is the experimental distribution.

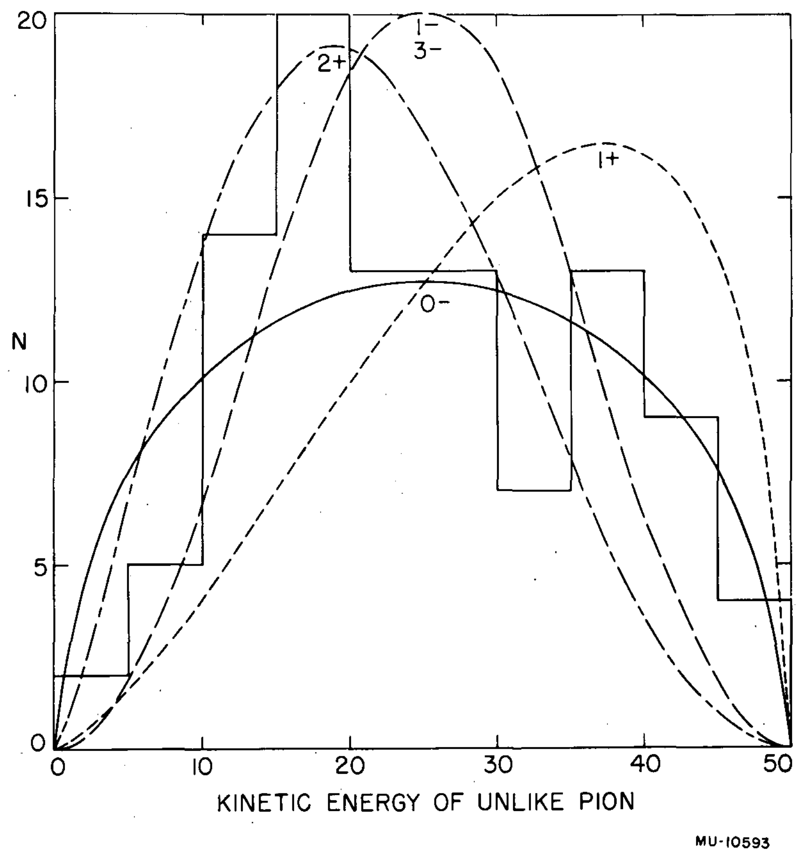

Fig. 3. Plot of expected odd-pion energy distributions for tau spin-parity 0-, 1+, 1-, 2+, 3-. Also shown is the experimental distribution.

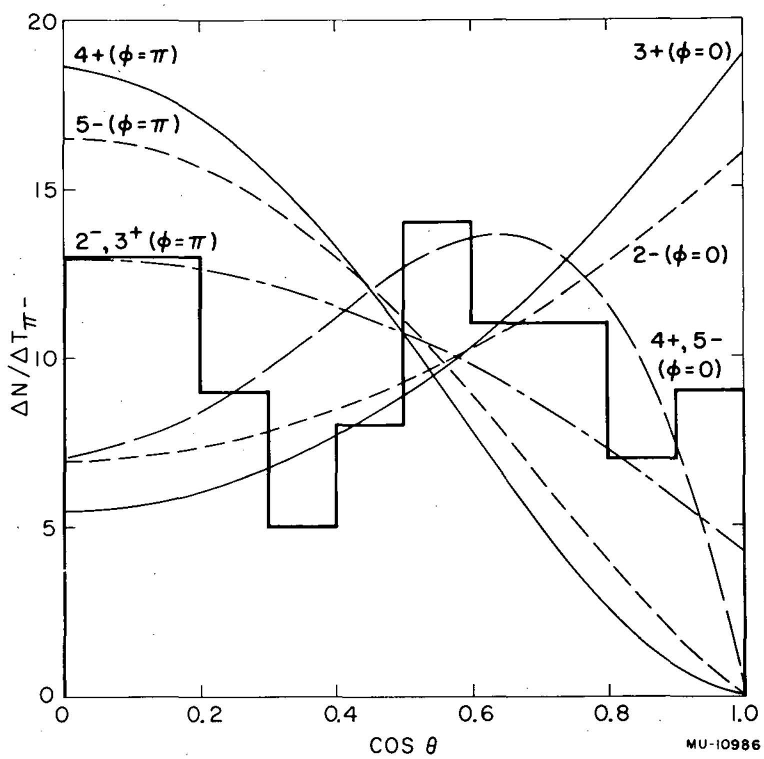

Fig. 4. Plot of expected cos θ distributions for tau spin-parity 2-, 3+, 4+, 5-. Here ϕ is the relative phase between competing three-pion states. The cases of 2- and 3+ for $\phi = \pi$ are very similar and are drawn as a single curve. In like manner the cases of 4+, 5- for $\phi = 0$ are very similar and are drawn as a single curve. Also shown is the experimental distribution.

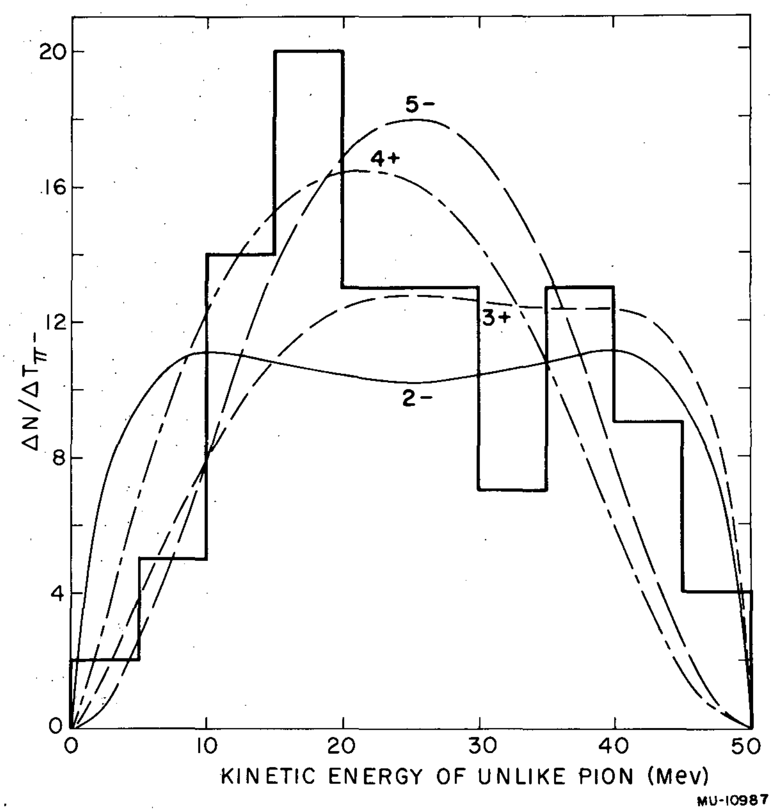

Fig. 5. Plot of expected odd-pion energy distribution for tau spin-parity 2-, 3+, 4+, 5-. Also shown is the experimental distribution.

Table I

Pearson probabilities for various values of spin and parity. Here ϕ is the relative phase between competing three-pion states.

Spin, parity		0-	1+	1-	2+	3-
Probability		$8 \cdot 10^{-2}$	$4 \cdot 10^{-8}$	$6 \cdot 10^{-31}$	$5 \cdot 10^{-11}$	$3 \cdot 10^{-6}$
Spin, parity			2-	3+	4+	5-
Probability	$\phi = 0$		$1 \cdot 10^{-4}$	$3 \cdot 10^{-6}$	$1 \cdot 10^{-4}$	10^{-3}
	$\phi = \pi$		$2 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$2 \cdot 10^{-28}$	10^{-12}

Table II

Power for various values of spin and parity (there are two powers for each case).

Spin, parity		1+	1-	2+	3-
Powers		0.95	0.9997	0.9945	0.9900
		0.995	1.0000	1.0000	0.9995
Spin, parity		2-	3+	4+	5-
Power	$\phi = 0$	0.55	0.915	0.82	0.87
			0.930	0.945	0.91
	$\phi = \pi$	0.55	0.65	0.9965	0.98
		0.65	0.76	1.0000	1.0000

C. Conclusion

Assume a 5% confidence level for the Pearson probability and a 95% confidence level for the power as the criteria for rejecting or accepting a case of spin-parity. Inspection of Tables I and II shows that 0- is the only case that is compatible with both requirements. The cases of 1-, 2+, and 3- must be rejected. The case of 1+ is on the border line, but 2-, 3+, 4+, and 5- clearly cannot be rejected.

For the tau and $K_{\pi 2}$ to have compatible spin and parity the tau must have parity $P = (-1)^J$, i.e., either 1-, 2+, 3-, 4+, 5-, etc. For these cases only 4+ and 5- are significantly probable.

ACKNOWLEDGMENTS

This paper is one aspect of a systematic investigation of positive K particles by Dr. Robert W. Birge, Dr. Donald H. Stork, Dr. Marian V. Whitehead, Mr. Leroy T. Kerth, Mr. James R. Petersen, Mr. Jack Sandweiss and the author, using the strong-focusing spectrometer at the Bevatron, whose design and implementation is due to Mr. Kerth and Dr. Stork. I wish to thank Dr. Birge, Dr. Stork, and Dr. Whitehead for their contributions and suggestions in the course of this work; Dr. Dan H. Holland for assistance in writing the section on tau-decay theory; our scanners, Mrs. Beverly Baldridge, Miss Irene D'Arche, Mrs. Edith Goodwin, Mrs. Marilyn Harbert, and Miss Kathryn Palmer; Mr. Victor Cook, and George Preston for their assistance with the measurements; and Dr. Edward J. Lofgren and the crew at the Bevatron.

This work was done under the auspices of the U. S. Atomic Energy Commission.

APPENDIX

A. Error in Q Due to Moisture Content

The error in Q due to an error in estimating the emulsion density to be $\rho_E = 3.826\ g/cm^3$ arises strictly from the difference in water content between the assumed and true values of the emulsion density. To estimate the effect of this error:

1. R_i, Z_i, R_{E_i}, Z_{E_i} are defined in Section III-4. R_{t_i} is the chord length for the true emulsion density ρ_t.
2. As in Section III-4, we have

   $R_{E_i}/R_i = Z_{E_i}/Z_i$, $R_{t_i}/R_i = Z_{t_i}/Z_i$ and

   $$\rho t = \sigma = \rho_E t_E = \rho_t t_t .$$

   Now we see, $R_{E_i}/R_{t_i} = Z_{E_i}/Z_{t_i} \simeq t_E/t_t = \rho_t/\rho_E$

   from which follows

   $$\sum_i R_{E_i} \simeq \rho_t/\rho_E \sum_i R_{t_i} \text{ or } R_E \simeq \rho_t/\rho_E\, R_t .$$

3. $dT/dx = \text{Const} \times n \times f(v)$, where n is the number of electrons per unit volume of emulsion. To within the accuracy of measurement the water and dry emulsion volumes are additive. Therefore n depends linearly on the emulsion density, i.e., $n = b\rho + d$. Barkas and Young[6] give $n = (0.2522\,\rho + 0.0830)\ 10^{24}/cm^3$ as the dependence of n on ρ. Now the range is

   $$R = \int_0^{T_0} dT/(dT/dx) = \frac{1}{\text{const.} \times n} \int_0^{T_0} dT/f(v), \therefore nR = g(v) .$$

   Assume for convenience that $T = a(Rn)^k$, where $k = \frac{1}{1.71}$. The range index k varies by about 14% over the region of interest; we have taken the mean value.

4. $T_t - T_E/T_E = \Delta T/T_E = (R_t n_t/R_E n_E)^k - 1 = (\rho_E n_t/\rho_t n_E)^k - 1.$

5. Assume $\rho_t = \rho_E + \Delta$ and make a Taylor's expansion of n_t/ρ_t about n_E/ρ_E. One obtains $n_t/\rho_t = n_E/\rho_E(1 - d\Delta\rho/n_E\rho_E)$. Then $\Delta T/T_E = (1 - d\Delta\rho/n_E\rho_E)^k - 1 \simeq kd\ \Delta\rho/n_E\rho_E$. Putting in the values

of k, d, and ρ_E given above, one obtains $\Delta T/T = -0.046\ \Delta\rho/\rho$.
Then we have

$$\sum_{L=1}^{3} \Delta T_i = \Delta Q = \sum_{L=1}^{3} (-0.046)\ \frac{\Delta\rho}{\rho}\ T_i = Q(-0.046)\ \Delta\rho/\rho, \text{ and}$$

$\Delta Q/Q = -0.046\ \Delta\rho/\rho$.

APPENDIX

B. Original Data on the τ^+ Particles

	Energies of π Secondaries				
Particle	π^+	π^+	π^-	Q	cos θ
16-5 P	46.0	11.4	17.3	74.7	.840
16-7 P	32.7	12.4	29.8	74.9	.478
16-36P	47.8*	17.6	9.5	74.9*	.888
16-40P	32.2	30.0	13.0	75.2	.057
16-51P	32.7	15.7	25.5	73.9	.398
16-85P	16.8	11.3	44.2	72.3	.239
16-86P	42.0	11.6	20.7	74.3	.718
16-103P	41.7*	28.0	5.2	74.9*	.519
16-123P	18.6	17.6	38.0	74.2	.028
16-131P	46.0*	20.0	8.9	74.9*	.784
16-163P	39.3	20.7	15.0	75.0	.469
16-181P	14.6	13.4	49.5	77.5*	.065
16-203P	39.5	17.5	18.2	75.2	.526
16-219P	30.0	9.0	35.8	74.8	.541
16-236P	21.7	14.2	39.1	75.0	.209
16-248P	42.2	21.6	11.6	75.4	.563
16-273P	31.2	23.4	21.3	75.9	.180
16-279P	42.2	6.4	25.7	74.3	.836
16-297P	30.2	12.3	31.3	73.8	.436
16-298P	28.5	2.7	43.7*	74.9*	.902
16-307P	35.3	21.4	17.6	74.3	.338
16-308P	39.0	17.2	18.7	74.9*	.521
16-311P	31.5	22.0	20.5	74.0	.226
16-312	32.2	12.4	28.9	73.5	.474
16-315P	18.6	14.5	40.9	74.0	.126
16-328	17.2	11.5	44.3	73.0	.237
16-336	41.3	13.9	20.0	75.2	.644
16-338	20.7	13.9	39.6	74.2	.199
16-349	38.0	34.5	3.9	76.4	.150
16-τA1	31.4	12.3	30.2	73.9	.461
16-τA2	24.0	13.0	38.7	75.7	.297
16-τA3	14.4	13.0	47.5*	74.9*	.072
16-τA5	43.1	4.9	25.9	73.9	.896
16-N1	31.2	28.8	14.8	74.8	.060
16-N10	34.6	8.8	32.5	75.9	.614
16-N20	38.3	16.9	19.5	74.7	.509
16-N23	29.7	29.1	16.7	75.5	.015
16-N32	19.6	17.5	38.2	75.3	.056
16-N80	43.7	18.0	13.0	74.7	.679
16-N84	43.0	23.0	9.8	75.8	.578
16-N89	20.1	12.2	42.6*	74.9*	.258

P: These tau's were included in the data presented at the Pisa Conference, 1955.

* One of the π's left the stack or made a large-angle scatter.

Energies of π secondaries (continued)

Particle	π^+	π^+	π^-	Q	cos θ
16-N119	37.6	7.9	30.2	75.7	.695
16-N129	30.1	18.7	26.5	75.3	.264
16-N145	31.0	1.6	43.2	75.8	.955
16-N149	39.0	15.0	20.9*	74.9*	.563
16-N162	36.0	36.0	1.9	73.9	0
16-N194	32.6	25.3	17.7	75.6	.176
16-N197	28.6	23.3	25.5	77.4	.118
16-N210	35.0	28.9	12.7	76.6	.161
16-N214	39.3	5.4	30.7	75.4	.798
16-N225	44.9*	3.4	26.6	74.9*	.962
16-N241	47.2	7.8	20.0	75.0	.928
17-1	39.5	7.0	27.5	74.0	.765
17-7	37.9*	25.9	11.1	74.9*	.333
17-40	27.9*	20.0	27.0	74.9*	.182
17-42	32.2*	27.0	15.7	74.9*	.130
17-47	42.7	17.0	15.8	75.5	.635
17-90	45.4*	9.5	20.0	74.9*	.847
17-97	29.8*	14.5	30.6	74.9*	.362
17-115	46.0*	7.1	21.8	74.9*	.906
17-145	29.3	24.5	20.5	74.3	.113
17-152	46.3*	8.4	20.2	74.9*	.892
17-170	35.6	16.8	24.0	76.4	.427
17-187	40.5	16.5	18.5	75.5	.572
17-188	30.4*	26.4	18.1	74.9*	.094
17-193	43.2	9.0	23.6	75.8	.783
17-204	19.3	12.1	43.5*	74.9*	.249
17-215	41.7*	22.0	11.2	74.9*	.546
20-111	20.2	20.1	36.2	76.5	.002
20-125	35.0	1.0	39.5	75.5	.948
20-165	24.5	7.4	43.0*	74.9*	.571
20-200	30.5	2.9	41.6	75.0	.854
20-233	44.2	21.2	10.8	76.2	.639
20-268	35.0	33.0	7.0	75.0	.068
20-270	33.8	29.0	12.8	75.6	.127
20-274	46.1*	18.0	10.8	74.9*	.790
20-283	22.8	18.9	32.2	73.9	.095
20-297	39.0	9.0	26.0	74.0	.702
20-383	46.0	18.6	10.8	75.4	.765
20-393	39.4*	21.1	14.4	74.9*	.467
20-397	38.0	18.3	15.5	71.8	.507
20-408	37.2	1.3	37.0	75.5	.933
20-446	32.4	27.1	15.0	74.5	.134
20-480	20.7	19.7	34.5	74.9	.026
20-497	36.5	1.6	36.8*	74.9*	.917

* One of the π's left the stack or made a large-angle scatter.

Energies of π secondaries (continued)

Particle	π^+	π^+	π^-	Q	cos θ
20-506	34.9	23.2	17.8	75.9	.280
20-518	47.2*	9.8	17.9	74.9*	.901
20-534	31.9	5.2	37.7	74.8	.719
20-552	41.6	20.2	13.3	75.1	.559
20-644	39.7	8.8	28.2	76.7	.699
20-699	31.0	6.3	37.0	74.3	.662
20-703	34.1	5.9	36.0	76.0	.709
20-707	30.5*	7.0	37.4	74.9*	.627
20-734	24.8	6.4	42.0	73.2	.630
20-749	43.4*	16.2	15.3	74.9*	.682
20-759	45.8	13.2	17.5	76.5	.777
20-768	33.0	26.0	16.0	75.0	.173
20-794	38.2	26.6	10.5	75.3	.328
20-859	35.8	10.9	29.2	75.9	.573
20-966	35.0	17.0	21.6	73.6	.429

* One of the π's left the stack or made a large-angle scatter.